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CFD Study of the Dust Dispersion in the 20L Explosion Sphere: Influence of the Nozzle Design

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The dispersion conditions of the powders in a 20 L sphere are standardized to obtain reproducible results during explosion tests. However, experimental and numerical investigations have demonstrated that the dust cloud is often heterogeneous and that the nominal dust concentration can be significantly different from that reached at the sphere centre when ignition occurs. In order to improve the dust cloud homogeneity, and consequently, to enhance the repeatability of the method, six alternative dispersion nozzles were designed and tested. The time evolution of the turbulence and of the particle size distribution of the dust cloud were determined respectively by particle image velocimetry and in situ laser diffraction sensor. Euler-Lagrange simulations (Star-CCM+) and DEM simulations were performed to study the dust dispersion dynamics and to assess the importance of the dust fragmentation/agglomeration. Explosion tests were also run for some selected nozzles. Results showed that the turbulence level in the sphere was always lower with the 6 symmetrical nozzles in comparison to the standard rebound nozzle. A lowest turbulent kinetic energy during ignition generally leads to a more homogeneous dust dispersion and thus to a concentration profile at the sphere centre which is closer to the nominal dust concentration. Nevertheless, this decay also implies lower explosion severities and sometimes results in dust accumulation within the nozzles. The particle size distribution of the dust cloud varies from that of the original powder, but does not significantly changes after the first milliseconds of its dispersion within the sphere. Moreover, particle fragmentation was nearly identical for all the nozzles. Numerical and experimental results then demonstrated that the fragmentation is both caused by the injection through the injection valve and by the nozzle geometry. As a consequence, a specific attention must be paid to the injection procedure and to the ignition delay time, which is directly related to the turbulence of the dust cloud.

1. Introduction

The main goal of standardization is to ensure that tests performed in different places, at different times and by different people will lead to comparable and reproducible results. In the context of the quantitative assessment of a dust explosibility, the dispersion conditions in a 20 L sphere were standardized by EN 14034 series (EN, 2011). However, previous experimental and numerical investigations have demonstrated that, at the moment of ignition, the dust cloud is far from being homogeneous (Di Benedetto et al., 2013; Di Sarli et al., 2013) and that the nominal dust concentration can be significantly different from that reached in the ignition zone (Murillo et al., 2018). As improving the dust cloud homogeneity is a key to enhance tests repeatability, six alternative dispersion nozzles were designed and their performances were studied both experimentally and numerically.

2. Materials and methods

2.1 Powder and experimental setups

Tests were performed on wheat starch and carbon black, with mean volume diameters of 60 and 15 µm, respectively. Explosion tests were performed in a standard 20 L sphere with 10 kJ chemical igniters. The time

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evolution of the turbulence and particle size distribution (PSD) was determined by in situ laser measurements (Helos - Sympatec) and particle image velocimetry (PIV) in a dispersion vessel similar to the 20 L vessel but equipped with windows (Murillo et al., 2018). In addition to the standard rebound nozzle (EN, 2011), six other nozzles were designed with various geometric characteristics (Figure 1). It should be noted that the nozzle 2 is distinguished from the standard system by its symmetrical shape.

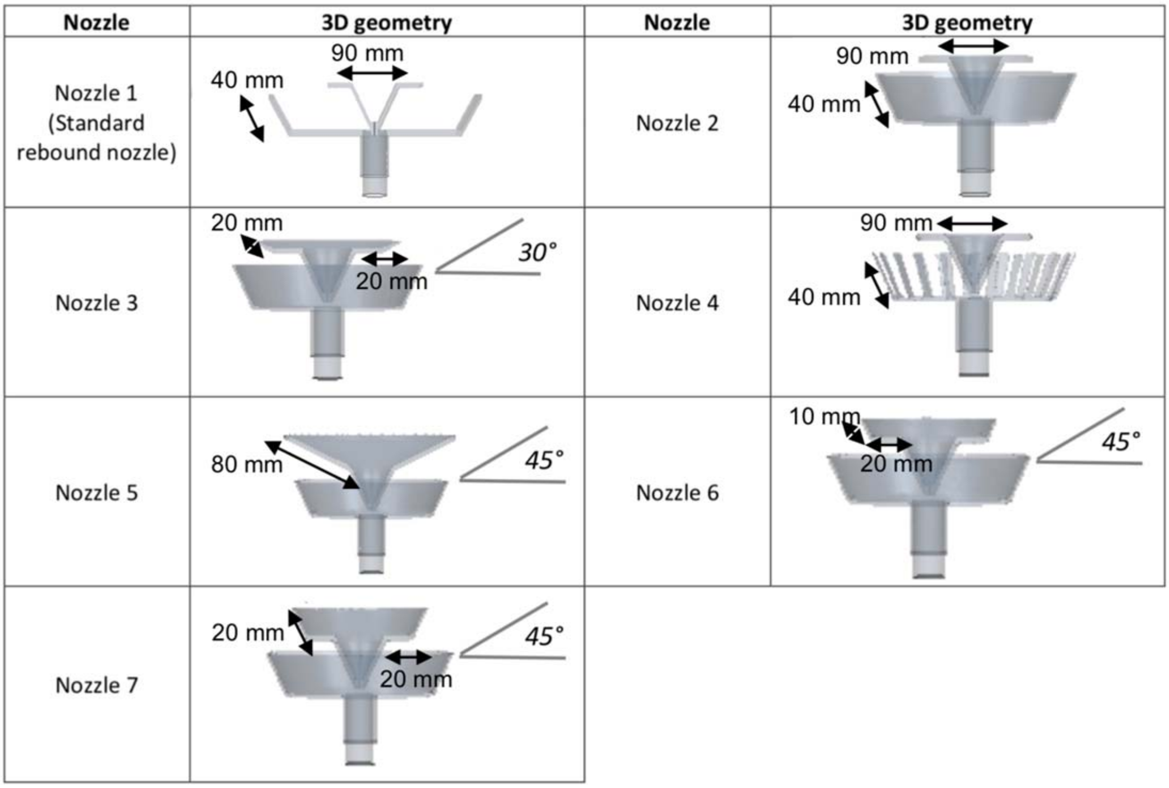

Figure 1: Description of the 7 nozzles used to disperse the powder within the 20 L sphere

2.2 CFD modelling

Euler-Lagrange simulations (Star-CCM+ V 12.02.010) were performed to study the dust dispersion dynamics whereas DEM simulations (Discrete Element Method) was applied for a predictive study of dust fragmentation and agglomeration. The Euler-Lagrange simulations were performed in transient state with a time-step set to obtain a Courant number of 1. For DEM simulations, a time-step of 1 µs at 5 iterations was required in order to ensure a fully convergence of the model. A total of approximately 3 million particles was represented. The turbulence of the dust cloud was described using a Detached Eddy Simulation (DES) model (Vizcaya et al., 2018). The validation of the CFD model was notably done by comparing the numerical results with the time evolution of the root-mean-square velocity and particle size distribution at the center of the sphere.

3. Results and discussion

3.1 Influence of the nozzle design on the turbulence level in the 20 L sphere

First, the pressure profiles in the 20 L sphere obtained numerically and experimentally were compared. An average error of 5% was recorded for all seven nozzles, which can be considered as satisfactory. The level of turbulence in the vessel before ignition was then studied because this parameter affects the PSD, through fragmentation or re-agglomeration phenomena, the dust cloud homogeneity and also the future flame propagation. The vector velocity field at 60 ms, i.e. at the standard ignition delay time tv, is shown in Figure 2 for the seven nozzles. It appears clearly that the use of the standard nozzle (nozzle 1) leads to higher gas velocities in the sphere, with regard to the other six nozzles. In such case, small particles will easily follow the gas flow and their spatial repartition will depend on that of the vector velocity field (Di Sarli et al., 2013). As a consequence, a poor homogeneity of the dust cloud is expected with the rebound nozzle. Nozzles 2, 3, 6 and 7 show lower velocity fields compared to nozzle 1, but with only slight changes between them.

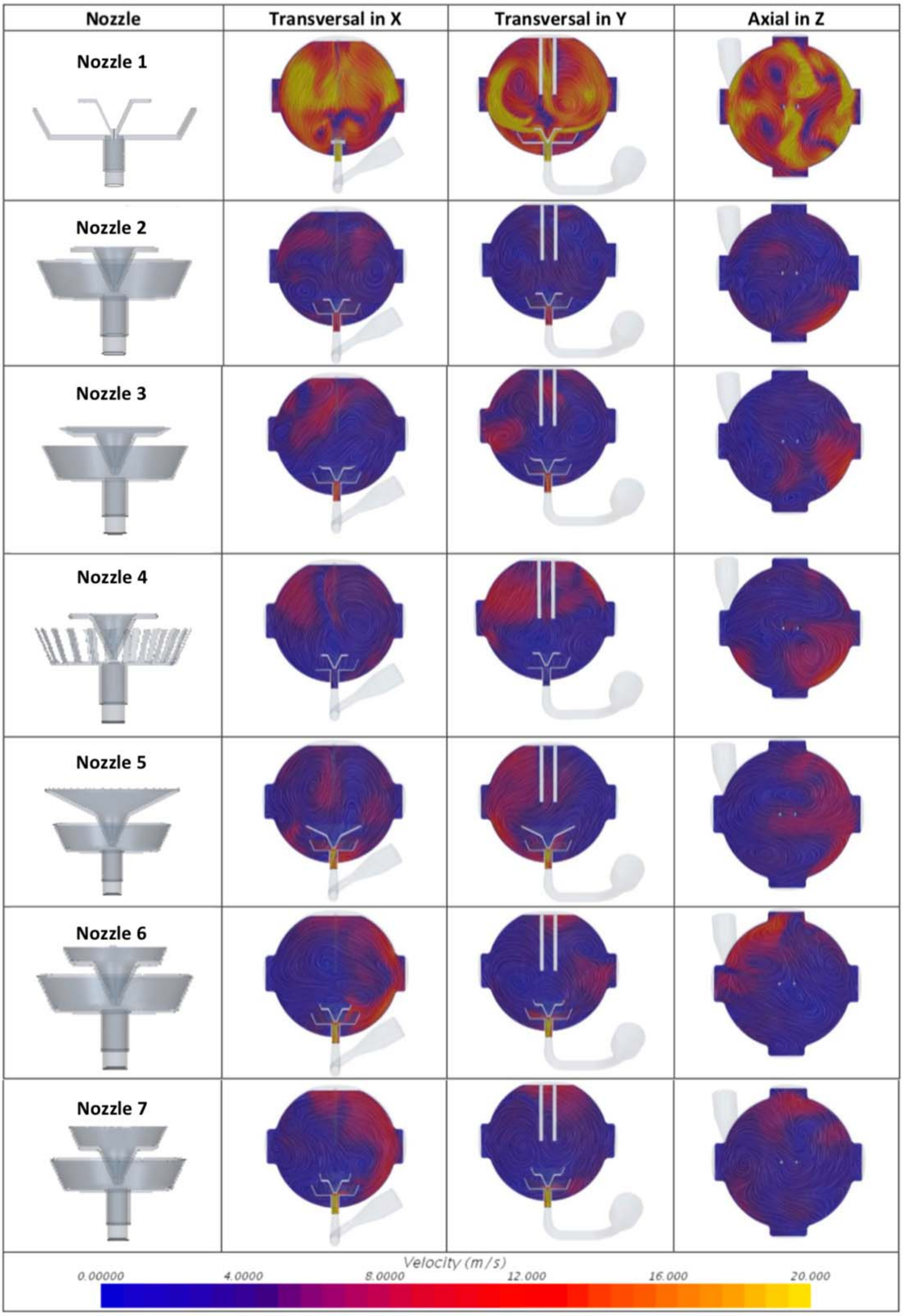

Figure 2: Vector velocity field profiles in the sphere at 60 ms for the seven different nozzles

In Figure 2, it can be noticed that the nozzle 4 generates higher velocity fields on the top and the opposite side of the dust container. Finally, both CFD simulations and PIV measurements demonstrate that the nozzle 5 generates an annular flow pattern that dissipates the energy more rapidly than the other nozzles.

3.2 Effect of the nozzle design on the dust dispersion

At first, experiments were performed by injecting starch in the 20 L sphere without any nozzle. It was demonstrated that the diameter d_{90} is significantly reduced, which shows that the greatest reduction of the size of the coarse agglomerates occurs in the solenoid valve, at the inlet of the sphere. CFD simulations confirmed that fragmentation cannot be attributed to the sole presence of a nozzle, but to the combination of the injection valve and the dispersion nozzle (Murillo, 2016). Such effects are due to the high local turbulence levels which are achieved in these regions owing to their high pressure gradients. It is consistent with the fact that particle or agglomerate breakage was observed by Sanchirico et al. (2015) at any conditions with the rebound and annular nozzles.

Figure 3 shows the flow pattern of carbon black cloud, at different times, using the seven nozzles. These results confirm that a slight modification of the nozzle geometry can significantly affect the flow pattern. The rebound nozzle (nozzle 1) leads to a ribbon flow pattern, when powders advance toward the walls and collide at the top center of the sphere, as already observed by Di Sarli et al. (2013) and Vizcaya et al. (2018). The other six nozzles present an annular flow pattern with some slight variations between each other. The particle size distribution of the dust cloud varies from that of the original powder, as verified experimentally, but does not significantly changes after 5 to 10 milliseconds of dust dispersion within the sphere. Moreover, particle fragmentation was nearly identical for the six alternative nozzles. Similar results were recorded with starch.

After 5 ms dispersion, a low dust concentration is clearly visible at the bottom of the sphere for the nozzles 2, 3, 4 and 5 (Figure 3). Nozzles 2, 4 and 5 even show some particle segregations at the early stages of the dispersion, which is usually the case after 60 or 120ms. It can also be noticed that the position of the dust container has an impact on the direction of rotation of the powder ribbons in the sphere. At 60 ms, nozzles 2 and 3 tend to accumulate the larger particles in the higher part of the sphere. More generally, the larger particles tend to remain in the zones of high velocities, which leads to particles segregation for nozzles whose velocity fields are greatly heterogeneous.

Focusing on the nozzle 1, it can be seen that the dust cloud is mainly concentrated at near the walls due to multiple vortices (Di Sarli et al., 2013), which implies a poor homogeneity of the dust cloud and a concentration at the center of the sphere, i.e. at the ignition zone, which is significantly different from the nominal dust concentration (Murillo et al., 2018).

The homogeneity of the dust cloud changes as a function of the time and the nozzle geometry. It appears that, for ignition delay times greater than 80 ms, the nozzle 2 gives the lowest difference between the dust concentration at the center of the sphere and the nominal dust concentration. However, for the standard ignition delay time, i.e. 60 ms, the nozzle 6 has the best performances in terms of dust cloud homogeneity: no dead volumes or areas of very high concentration can be seen. Nevertheless, PIV measurements show a greater decrease of the turbulence level in the sphere with the nozzle 6 than with the rebound nozzle. Generally, a lowest turbulent kinetic energy during ignition leads to a more homogeneous dust dispersion.

3.3 Impact of the nozzle design on the dust explosion severity

Explosion tests were carried out on wheat starch in the 20 L sphere with three of the seven nozzles: the standard one, the nozzle 2, due to its symmetry with respect to nozzle 1 and the nozzle 6, due to the homogeneity of the dust cloud generated at 60 ms. Results, especially the maximum rate of pressure rise $(dP/dt)_m$, are given in Figure 4 for various ignition delay times.

First, it appears that the maximum rates of pressure rise are only slightly different at low concentration, i.e. 125 $g.m^{-3}$, in particular at 60 ms. Nevertheless, at 110 ms, $(dP/dt)_m$ is greater with the nozzle 1 than with the other ones. At 500 $g.m^{-3}$, the maximum rate of pressure rise decreases when increasing the ignition delay time. Moreover, the explosion severity is greatly affected by the nozzle geometry; for instance, at 60 ms, $(dP/dt)_m$ can be reduced by a third when using nozzle 2 instead of the rebound nozzle. In most of the cases, the standard nozzle leads to the most conservative values. However, the experimental scattering of the data obtained with the nozzle 1 (Proust et al., 2007) is greater than with nozzle 2 and 6. The turbulence decay, observed previously, also implies lower explosion severities and can, with dense powders or at large concentrations, results in dust accumulation within the nozzles.

It should be underlined that the experimental repeatability is significantly increased by using the nozzles 2 (Murillo et al., 2018) and 6. At any tv, $(dP/dt)_m$ seems to be greater with the nozzle 6 than with the 'symmetric nozzle' 2. Further tests need to be performed on various powders before generalizing these comments. In all cases, for a given nozzle, a specific attention must be paid to the injection procedure and to the ignition delay time, which is directly related to the turbulence and homogeneity of the dust cloud.

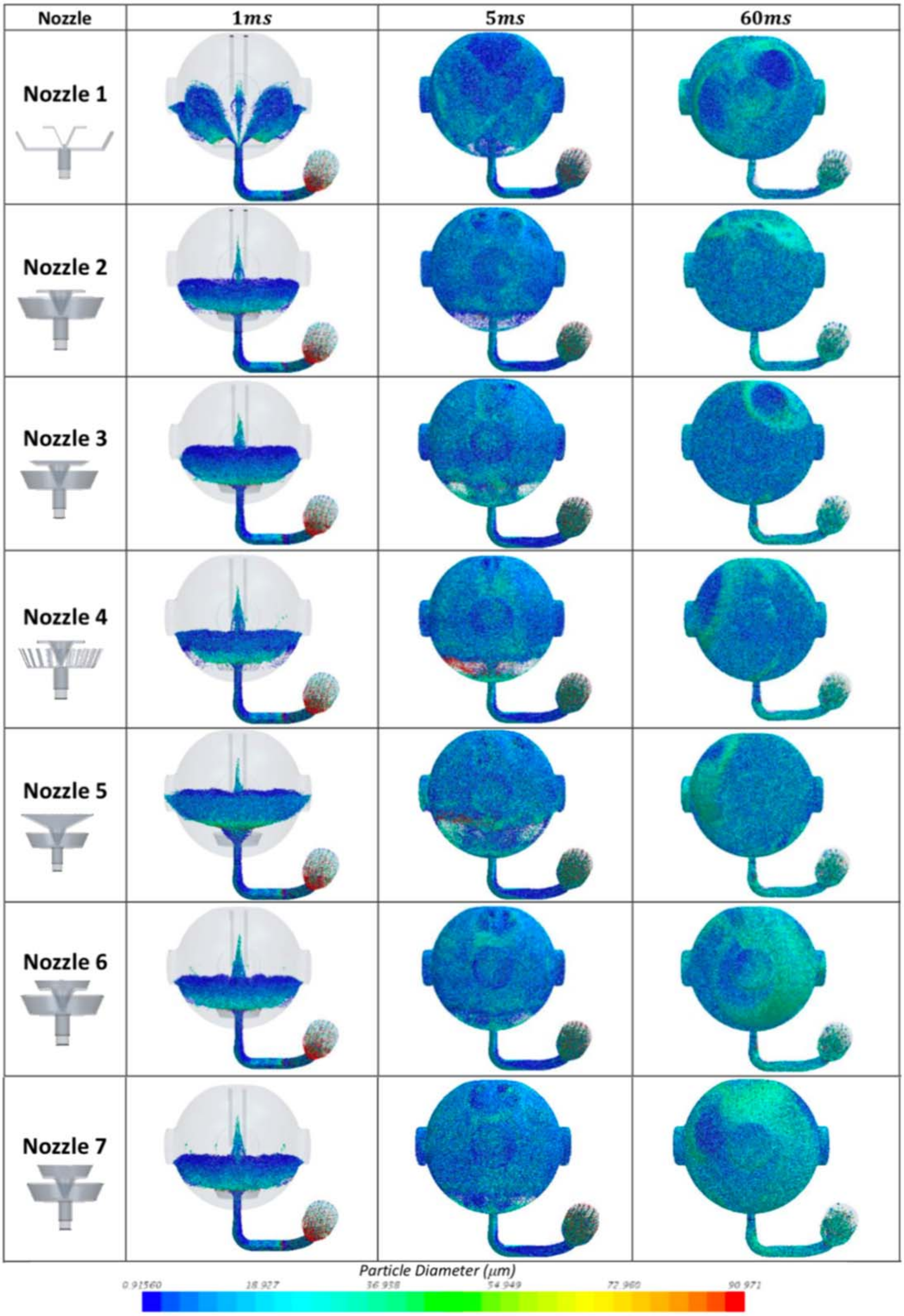

Figure 3: Carbon black dispersion profile at different times for the seven nozzles

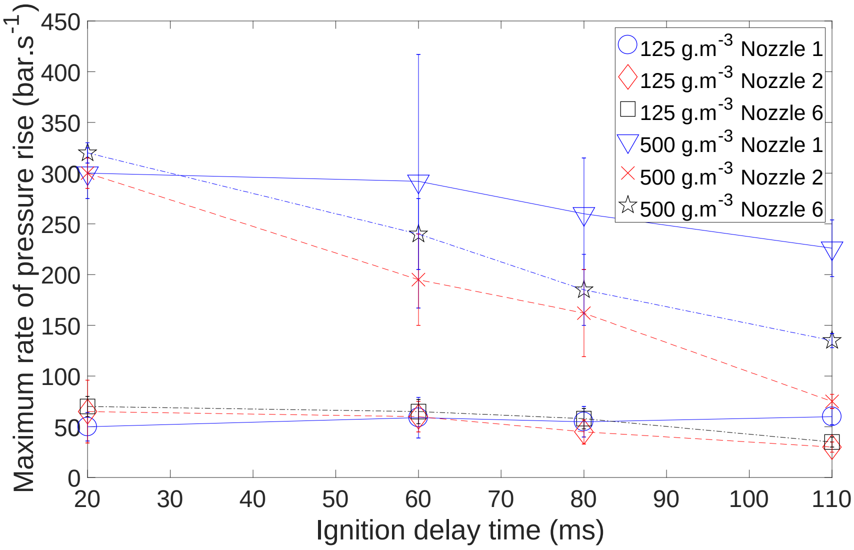

Figure 4: Evolution of the maximum rate of pressure rise of starch as a function of tv for various nozzles

4. Conclusions

Six alternative nozzles were designed and tested numerically and experimentally. Due to their symmetry, they usually produce a dust concentration at the ignition zone which is rather close to the nominal dust concentration. If the experimental repeatability is then increased, the use of such nozzles also increases the decay rate of the turbulence levels and often reduces the dust explosivity.

Nozzle 6 demonstrates the best performances in terms of dust homogeneity. However, it should be stressed that its use will lead to the necessary adaptation of the ignition delay time in order to get closer to the results obtained by following the standards. A similar work should also be performed on the determination of the minimum explosible concentration, but by considering lower ignition energies (2 kJ).

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